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Systematic Review

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Assessment of Hydro-geochemical and Radiological Contamination Associated with Artisanal and Small-Scale Gold Mining and Its Implications for Human Health and the Environmental Quality

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Graphical Abstract



Abstract

Background: Artisanal and small-scale gold mining (ASGM) is widely practiced across low- and middle-income countries and constitutes a major source of environmental contamination and public health risk. The use of mercury amalgamation, poor waste management practices, and the disturbance of mineralized host rocks contribute to the release of toxic heavy metals and naturally occurring radioactive materials (NORMs) into soils, surface water, and groundwater systems. **Objective:** This systematic review aimed to evaluate the

extent, pathways, and human health implications of geochemical, radiological, and hydrogeological hazards associated with ASGM activities, with particular emphasis on exposure risks to miners and surrounding rural communities. **Methods:** A systematic literature review was conducted using peer-reviewed journal articles, reports, and technical documents published over the last two decades. Studies addressing heavy metal contamination, radionuclide exposure, groundwater degradation, and associated health risks in ASGM environments were critically analyzed. Data were synthesized thematically under geochemical, radiological, and hydrogeological impact domains. **Results:** The review reveals consistently elevated concentrations of mercury, arsenic, lead, cadmium, and cyanide in soils and water bodies near ASGM sites, frequently exceeding international guideline limits. Radiological assessments indicate enhanced exposure to NORMs, particularly ^{226}Ra and ^{232}Th , among miners and local residents, raising long-term cancer risk concerns. Hydrogeological evidence demonstrates widespread groundwater contamination, aquifer vulnerability, and deterioration of potable water quality, with seasonal variability often overlooked. Methodological limitations across studies include small sample sizes, short monitoring durations, and inadequate integration of multi-hazard exposure pathways. **Conclusion:** ASGM activities pose significant and interconnected geochemical, radiological, and hydrogeological hazards that threaten environmental sustainability and public health. The cumulative and long-term nature of these risks necessitates integrated assessment frameworks, strengthened regulatory oversight, and the implementation of sustainable mitigation strategies to protect vulnerable populations.

Keywords: Artisanal and small-scale gold mining, Mercury, Cyanide, Radionuclides, Norms, Groundwater, Health risks

1. Introduction

Artisanal and small-scale gold mining (ASGM) is a widespread informal mining activity that provides livelihoods for millions of people, particularly in developing regions of Africa, Asia, and South America. Despite its socio-economic relevance, ASGM is frequently characterized by unregulated extraction practices, poor environmental management, and limited awareness of environmental and health consequences. Gold-bearing ores often occur in association with toxic trace elements such as mercury (Hg), arsenic (As), lead (Pb), and cadmium (Cd), as well as naturally occurring radioactive materials (NORMs) including uranium (^{238}U), thorium (^{232}Th), and potassium (^{40}K). The disturbance of geological formations during mining enhances the mobilization of these contaminants into surrounding environmental media [1,2]

One of the most critical environmental concerns associated with ASGM is the contamination of soil and groundwater systems. Excavation, ore processing, tailings disposal, and mercury amalgamation facilitate the leaching of heavy metals and radionuclides into surface water and shallow aquifers, which are often the primary sources of drinking water in mining communities. Hydrogeological studies have shown that groundwater in ASGM areas frequently exceeds international guideline limits for toxic elements, posing serious long-term health risks [3,4]. In addition to chemical toxicity, exposure to ionizing radiation from NORMs contributes to cumulative radiological risks that are rarely assessed alongside chemical hazards [5]. Human exposure to ASGM-related contaminants occurs through multiple pathways, including ingestion of contaminated water and food crops, inhalation of dust, and dermal contact with polluted soils. Numerous studies have applied health risk assessment models to estimate non-carcinogenic and carcinogenic risks; however, findings remain fragmented across disciplines and regions [6]. The lack of integrated synthesis limits effective risk communication, regulatory enforcement, and mitigation planning.

Therefore, a systematic literature review integrating **geochemical, radiological, hydrogeological, and human health risk evidence** is necessary to provide a comprehensive understanding of ASGM-induced hazards. The main objective of this work is to synthesize global evidence using a PRISMA-based approach, identify dominant contamination trends, evaluate exposure pathways, and highlight critical research gaps to inform sustainable mining policies and public health interventions. The organization of this article comprised of Abstract, Introduction, Related work, Material & Method, Results & Discussion Sections

2. Related Work

Artisanal and small-scale gold mining (ASGM) has been widely reported as a major source of geochemical contamination in mining communities due to the release of potentially toxic elements such as mercury (Hg), arsenic (As), lead (Pb), cadmium (Cd), zinc (Zn), and other trace metals into soils, sediments, and water systems. In Ghana, studies have demonstrated elevated concentrations of Hg and As in soils and sediments in mining districts such as Obuasi, with contamination levels exceeding international guideline limits and posing significant ecological and human health risks [1]. Mercury exposure among miners and nearby residents has been documented through environmental sampling and biological monitoring, indicating neurotoxic and renal implications [1,2]. Similarly, in Nigeria, investigations in Zamfara State (Anka and Maru areas) revealed severe contamination of soils and surface waters with Pb, Cd, Cu, and Zn due to uncontrolled gold ore processing activities, resulting in documented cases of acute lead poisoning and long-term environmental degradation [3]. Heavy metal pollution has also been reported in river systems such as the Osun River, where mining-related discharges contribute to water quality deterioration and bioaccumulation risks [4]. These findings demonstrate that ASGM significantly alters geochemical baseline conditions and introduces persistent contaminants into terrestrial and aquatic environments.

Radiological contamination associated with ASGM has gained increasing attention, particularly in regions where gold ores are associated with naturally occurring radioactive materials (NORMs). In Cameroon, environmental assessments have highlighted the mobilization of radionuclides through mining excavation and waste deposition processes, although radiological characterization remains limited compared to geochemical studies [5]. In Kenya, investigations in West Pokot County assessed both heavy metal concentrations and radio-ecological hazards linked to artisanal gold mining, reporting elevated gamma dose rates and radionuclide activity concentrations in mining areas [6]. These studies emphasize that mining activities can enhance exposure to radionuclides such as radium-226 and thorium-232 through dust inhalation, soil ingestion, and external gamma radiation. Similarly, across West African countries including Senegal, the continued use of mercury amalgamation has been associated with widespread environmental dispersion of toxic substances, with emerging concerns about combined chemical and radiological exposures in mining communities [7]. Globally, reviews indicate that ASGM remains one of the largest anthropogenic sources of mercury emissions, contributing substantially to environmental contamination and associated radiological risk interactions [8,9].

Hydrogeological impacts of ASGM further exacerbate environmental degradation by altering groundwater flow dynamics and contaminating aquifers. Excavation pits, tailings dumps, and unregulated dewatering practices disrupt natural recharge systems and increase sediment loading into nearby water bodies. Hydrogeochemical analyses in several African mining regions demonstrate elevated heavy metal concentrations in groundwater systems adjacent to mining sites, compromising potable water sources for rural populations [3,5]. The interaction between contaminated surface water infiltration and fractured bedrock aquifers enhances the mobility of toxic elements, increasing long-term exposure risks. Collectively, evidence from Ghana, Nigeria, Cameroon, Kenya, Senegal, and other global mining regions indicates that ASGM produces integrated geochemical, radiological, and hydrogeological disturbances that significantly threaten environmental quality and public health. Despite growing documentation, research remains fragmented, underscoring the need for integrated multi-disciplinary risk assessment frameworks and strengthened regulatory interventions.

The reviewed studies demonstrate that ASGM activities consistently elevate concentrations of toxic metals, most notably mercury (Hg), arsenic (As), lead (Pb), cadmium (Cd), and copper (Cu) in environmental compartments including soils, surface waters, groundwater, sediments, crops, and aquatic biota [7,8,9,10]. In many cases, reported concentrations exceeded internationally accepted guideline values, underscoring the significance of ASGM as a major source of environmental degradation [11,12,13].

3. Materia and Method

3.1. Review Design and Framework

This study adopted a **systematic literature review design** guided by the **Preferred Reporting Items for Systematic Reviews and Meta-Analyses [14]** framework. PRISMA provides a transparent and reproducible method for identifying, screening, and synthesizing existing research evidence, ensuring methodological rigor and minimizing selection bias [15].

3.2 Search Strategy

A comprehensive literature search was conducted across multiple electronic databases to capture peer-reviewed and authoritative studies on ASGM-related environmental and health hazards. The databases included: Scopus, Web of Science, ScienceDirect, PubMed, SpringerLink, ResearchGate, Academia and Google Scholar. The search covered studies published from **2000 to 2024**, reflecting the period of increased global attention to ASGM-related environmental and health impacts.

3.3 Search Terms and Keywords

Search terms were developed using a combination of **keywords and Boolean operators**, structured around four thematic domains: mining activity, environmental contamination, hydrogeology, and health risk. **The Core search string included:** “artisanal gold mining” OR “small-scale gold mining” AND “heavy metals” OR “geochemical contamination” OR “mercury” OR “arsenic”AND “natural radionuclides” OR “radiological hazard” OR “NORM” AND “groundwater contamination” OR “hydrogeology” AND “health risk assessment” OR “human exposure”. These terms were adapted slightly across databases to optimize retrieval sensitivity.

3.4 Eligibility Criteria

The eligibility criteria for the selection of the studies were tabulated in the table 1 below:

Table 1: Eligibility criteria

Category	Criteria
Inclusion Criteria	❖ Peer-reviewed journal articles ❖ Studies focused on Artisanal and Small-Scale Gold Mining (ASGM) environments ❖ Research reporting heavy metals, radionuclides, groundwater quality, or health risk indices ❖ Studies published in English
Exclusion Criteria	➤ Studies exclusively on large-scale industrial mining activities ➤ Editorials, commentaries, and conference abstracts lacking full datasets ➤ Studies without adequate quantitative analysis or clear methodological description

3.5 Study Selection Process

All retrieved records were exported to a reference management software, and duplicates were removed (fig.1) . Titles and abstracts were independently screened for relevance. Full-text articles were subsequently assessed against eligibility criteria. The selection process followed the PRISMA flow sequence: **identification, screening, eligibility, and inclusion** [15,16]. The PRISMA flow chart for the study selection is given below in figure 1

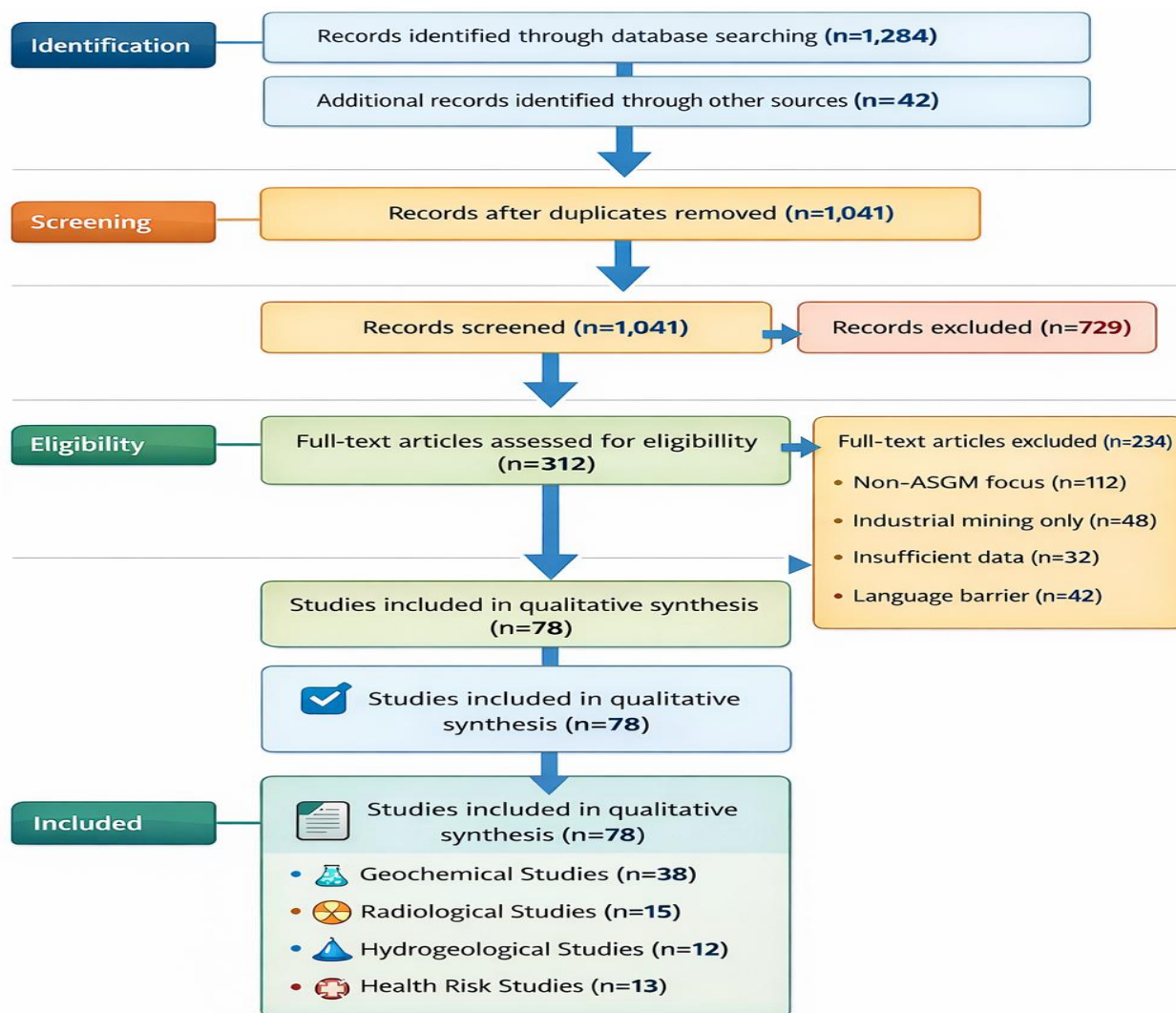


Figure 1: PRISMA flow chart

3.6 Data Extraction

A standardized data extraction template was developed to ensure consistency across studies. Extracted information included: Author(s) and Year of Publication, Title of Study, Study Location, Study Design and Methods (sampling media, analytical techniques, models used), Key Findings (contaminant levels, radiological indices, groundwater quality parameters), Conclusions and Identified Research Gaps [17,18]. This structured extraction enabled comparative analysis across geographical regions and methodological approaches. Below is the structured data table used

Author (Year)	Title of Study	Study Location	Study Design and Methods	Key Findings	Conclusions	Identified Gaps

3.7 Data Synthesis

3.7.1 Narrative and Thematic Synthesis

Given the heterogeneity of study designs, analytical methods, and reported indices, a **narrative synthesis approach** was adopted. Studies were grouped into four thematic categories: Geochemical contamination (heavy metals), Radiological hazards (NORMs and dose indices), Hydrogeological and groundwater impacts and Human exposure pathways and health risks. Within each theme, findings were synthesized descriptively to identify dominant trends, ranges of contaminant concentrations, and commonly reported risk indices.

3.7.2 Comparative and Gap Analysis

Comparisons were made across regions to highlight geographical patterns and vulnerability hotspots. Methodological similarities and differences, including sampling strategies and risk assessment models, were critically examined to assess data robustness. Special attention was given to identifying **knowledge gaps**, including: Limited integration of radiological and chemical risk assessments, Scarcity of long-term groundwater monitoring studies and Underrepresentation of cumulative and synergistic health effects

3.8 Ethical Considerations

As this study relied solely on published literature, no ethical approval was required. However, all sources were appropriately cited to maintain academic integrity.

4. Results and Discussion

4.1 Results Overview from the literatures

The synthesized evidence presented in Table 2 provides a comprehensive overview of geochemical contamination by heavy metals associated with artisanal and small-scale gold mining (ASGM) across diverse geographical regions. Collectively, the reviewed studies demonstrate that ASGM activities consistently elevate concentrations of toxic metals, most notably mercury (Hg), arsenic (As), lead (Pb), cadmium (Cd), and copper (Cu) in environmental compartments including soils, surface waters, groundwater, sediments, crops, and aquatic biota [7,8,9,10]. In many cases, reported concentrations exceeded internationally accepted guideline values, underscoring the significance of ASGM as a major source of environmental degradation [11,12,13]

4.1.1 Geochemical Characteristics and Distribution of Heavy Metals

A consistent finding across the reviewed studies is the strong spatial association between mining and ore-processing zones and elevated heavy metal concentrations. Investigations conducted in ASGM hotspots such as Obuasi (Ghana), Zamfara State (Nigeria), and Guizhou Province (China) reported extreme enrichment of Hg and As in soils and sediments proximal to amalgamation sites and tailings dumps [11,12 & 13]. Riverine studies further highlighted the role of surface runoff and sediment transport in redistributing contaminants downstream, thereby extending the spatial footprint of ASGM pollution beyond immediate mining areas [11,12 & 19]. These findings confirm that ASGM functions both as a point source and a diffuse source of heavy metal contamination through hydrological and atmospheric dispersion pathways [20,21].

From a methodological standpoint, the studies summarized in Table 2 predominantly employed field-based environmental sampling combined with laboratory geochemical analyses, including Atomic Absorption Spectrophotometry (AAS), Inductively Coupled Plasma–Mass Spectrometry (ICP-MS), and mercury speciation techniques [8,9 & 22]. Many studies integrated pollution indices such as contamination factor, geoaccumulation index, and pollution load index to quantify contamination severity [10, 23]. More recent investigations also applied human health risk assessment models, including hazard quotient (HQ), hazard index (HI), and incremental lifetime cancer risk (ILCR), reflecting a shift toward risk-based assessment frameworks [24,25]. The reviewed literature provides compelling evidence that ASGM-derived heavy metals pose significant ecological and public health risks. Several studies documented metal accumulation in crops and fish, indicating active transfer through terrestrial and aquatic food chains [11, 19,26]. Human health risk assessments consistently reported non-carcinogenic risks exceeding acceptable thresholds and elevated carcinogenic risks, particularly for arsenic exposure in mining communities [24,25]. Review-based and epidemiological studies further emphasized that children and women are disproportionately vulnerable to mercury exposure in ASGM settings [27,28]. Despite regional and methodological differences, the conclusions drawn across the reviewed studies are remarkably consistent. The literature strongly agrees that unregulated or poorly managed ASGM activities result in persistent environmental contamination and long-term health risks [29,30,31]. Policy-oriented and review-based studies emphasized that technological interventions, such as mercury retorts and cleaner processing techniques, while beneficial, are insufficient in isolation [29,31,33]. Sustainable mitigation requires integrated strategies combining technological innovation, regulatory enforcement, socioeconomic considerations, and community engagement [34&2]

Notwithstanding the robustness of existing evidence, several critical gaps were identified. Many studies relied on cross-sectional designs, limiting insight into temporal trends and cumulative exposure effects [31]. Groundwater contamination remains comparatively under-investigated relative to soils and surface waters, particularly in semi-arid ASGM regions [10,22]. Furthermore, there is a scarcity of biomonitoring studies linking environmental concentrations to internal human exposure levels [35,36]. Few investigations assessed remediation effectiveness, and interactions between heavy metals and naturally occurring radionuclides are rarely addressed [20,37]. Overall, the evidence synthesized in Table 2 underscores the urgent need for integrated, risk-informed approaches to ASGM research and management. Future studies should prioritize long-term monitoring, comprehensive exposure pathway analysis, biomonitoring, and evaluation of remediation strategies [38,39]. Addressing these gaps will enhance scientific understanding and support evidence-based policy formulation, particularly in rapidly expanding ASGM regions of sub-Saharan Africa.

Table 2: Geochemical contamination of ASGM

Author (Year)	Title of Study	Study Location	Study Design & Methods	Key Findings	Conclusions	Identified Gaps
[7]	Arsenic pollution at Obuasi goldmine	Obuasi, Ghana	Soil & water sampling; AAS analysis	Elevated As above WHO limits in soils and water	Gold mining significantly contributes to arsenic pollution	No health risk quantification
[8]	Mercury contamination from ASGM	Mindanao, Philippines	Environmental sampling; Hg speciation	High Hg in sediments and biota	ASGM is a dominant Hg pollution source	Limited temporal analysis
[9]	Heavy metals from gold mining	Birim North, Ghana	Soil & water sampling; ICP-MS	As, Pb, Cd exceed background levels	Mining alters local geochemistry	No exposure pathway modeling
[10]	Heavy metals in ASGM soils	Zamfara, Nigeria	Soil geochemistry; pollution indices	High Pb, Cd, Hg with extreme pollution indices	ASGM responsible for severe soil degradation	No groundwater assessment
[11]	Mercury in Pra River Basin	Ghana	Water, sediment, fish sampling	Bioaccumulation of Hg in fish	ASGM impacts aquatic ecosystems	No dietary risk estimation
[12]	Mercury in rivers near ASGM	Ghana	Water & sediment analysis	Hg exceeds WHO limits	Rivers serve as contamination pathways	Seasonal variation ignored
[13]	Global mercury assessment	Global	Emission inventory & modelling	ASGM is largest Hg source	Urgent global intervention needed	Local exposure details missing
[19]	Mercury in Lake Victoria fish	Tanzania	Fish tissue analysis	Elevated methyl-Hg in fish	Mining affects regional food safety	No link to specific ASGM sites
[20]	Metals from mining activities	Global	Conceptual geochemical review	Mining mobilizes toxic metals	Long-term persistence emphasized	ASGM context not explicit
[21]	Mercury pollution from mining	Guizhou, China	Soil, water & air monitoring	Extreme Hg enrichment near mines	ASGM drives regional Hg cycling	Atmospheric transport understudied
[22]	Heavy metals in ASGM soils	Sudan	Soil sampling; contamination indices	High Pb, As, Cd pollution	Uncontrolled ASGM degrades soils	No remediation framework
[23]	Metals in soil and dust	Nigeria	Soil/dust sampling; PCA	Pb and Cd dominate contamination	Inhalation exposure is significant	Indoor exposure not assessed
[24]	Cancer risk from soil metals	Obuasi, Ghana	Human health risk modeling	Elevated cancer risk from As	Long-term exposure is hazardous	Limited population coverage

[25]	Health risks in ASGM communities	Ghana	Risk indices (HQ, HI)	Non-carcinogenic risks exceed limits	Residents face serious health threats	No biomonitoring data
[26]	Metals in soils and vegetation	Obuasi, Ghana	Soil-plant sampling; AAS	Elevated metal uptake in crops	Food chain contamination evident	No human risk modeling
[29]	Environmental impact of ASGM	Ghana	Policy & environmental assessment	Land degradation and metal pollution	ASGM requires regulatory reform	Quantitative geochemical data lacking
[30]	Heavy metal pollution from gold mines	Global	Review of soil & microbial studies	Persistent metals (Hg, Pb, As) dominate	Biogeochemical cycling enhanced by mining	Limited ASGM-specific remediation
[31]	Heavy metals in ASGM landscapes	Sub-Saharan Africa	Comparative synthesis	Metals persist in soils and waters	ASGM contamination is widespread	Few longitudinal studies
[32]	Clean artisanal gold mining	Global	Field trials & review	Cleaner techniques reduce Hg	Sustainable ASGM is feasible	Long-term monitoring absent
[33]	Mercury consumption in ASGM	Global	Mass balance analysis	Hg losses extremely high	ASGM inefficiency worsens pollution	Alternative tech adoption limited
[34]	Mercury & marginalization	Ghana	Socio-environmental analysis	Hg risk intertwined with poverty	Technical solutions alone insufficient	Limited geochemical quantification
[35]	Spatial Hg exposure patterns	Ghana	GIS-based exposure assessment	High exposure near processing sites	Spatial tools useful for ASGM risk	Limited metal diversity
[37]	Environmental management of ASGM	Dumasi, Ghana	Soil, sediment analysis; field surveys	Elevated Hg and Pb in mine zones	Poor mining practices increase contamination	Lack of remediation assessment
[39]	Global Hg emissions from ASGM	Global	Emission modelling	ASGM dominates anthropogenic Hg	Global policy relevance	Regional uncertainty remains
[40]	Mercury hazards from gold mining	Global review	Literature synthesis	Hg toxic to humans and ecosystems	ASGM is a major Hg emission source	No regional quantification
[41]	Mercury abatement in ASGM	Global	Policy & technology review	Retorting reduces Hg emissions	Technology adoption is low	Socioeconomic barriers unaddressed
[42]	Hg contamination in ASGM zones	Guizhou, China	Multi-media sampling	Hg accumulates in sediments	ASGM impacts entire catchments	No remediation trials

4.1.2 Radiological Contamination

The studies summarized in Table 3 provide a comprehensive evaluation of the environmental and radiological risks associated with artisanal and small-scale gold mining (ASGM) across Africa and other global contexts. The body of evidence highlights two primary areas of concern: exposure to naturally occurring radioactive materials (NORM) and chemical contamination, particularly heavy metals such as mercury (Hg), lead (Pb), and cadmium (Cd). Collectively, these studies demonstrate that ASGM activities significantly impact both human health and the environment. Several investigations, including Bello et al.

[43] and Pkemoi et al.[44], employed RESRAD and ERICA modeling alongside in-situ radiological measurements to estimate radiological doses and excess lifetime cancer risks in Northern Nigeria and West Pokot, Kenya. Findings from these studies consistently indicate that miners and nearby populations may experience annual effective doses and cancer risks exceeding recommended safety thresholds, suggesting that ASGM contributes substantially to localized radiation exposure. Despite the methodological rigor, these studies primarily focused on radiological hazards, often omitting concurrent chemical contamination assessments, which limits understanding of cumulative exposure effects. Other studies, such as Kolo et al. [45] and Girigisu et al. [46], utilized gamma spectrometry to quantify activity concentrations of radionuclides, including ^{226}Ra , ^{232}Th , and ^{40}K . Elevated activity concentrations and hazard indices were reported, with some measurements approaching or exceeding recommended limits. These findings underscore the necessity of continuous radiological monitoring in high-activity ASGM zones. However, limitations identified include the lack of integration with heavy metal analyses, absence of bioaccumulation assessments in crops or water, and limited human biomonitoring, suggesting that radiological assessments alone may underestimate overall environmental and health risks.

Complementary research on chemical contamination provides critical insight into the health and ecological implications of ASGM. Systematic reviews, such as Allan-Blitz et al. [47], reveal that children in ASGM regions are particularly vulnerable to exposure to Hg, Pb, and particulate matter, emphasizing significant public health concerns. Field-based studies, including Barde et al. [48] and Elwaleed et al. [49], demonstrate that heavy metal concentrations in soils and water frequently exceed WHO or international limits, posing moderate to high ecological risks and indicating substantial environmental contamination. Despite these contributions, gaps remain, including limited longitudinal data, insufficient spatial coverage, and lack of integrated human health risk assessments, which collectively hinder a comprehensive understanding of exposure dynamics. Narrative reviews, such as Ondayo et al. [50] and Veiga et al. [59], contextualize these findings by synthesizing decades of research on ASGM-related pollution, deforestation, and occupational hazards. These reviews highlight that although interventions to mitigate mercury exposure have achieved localized successes, global monitoring remains fragmented, and community-level implementation strategies are insufficiently documented.

Overall, the current literature demonstrates that ASGM presents a dual hazard of radiological and chemical contamination, yet most studies examine these risks in isolation. Radiological investigations rarely incorporate heavy metal assessments, and chemical studies seldom consider radiological exposure, revealing a critical gap in multidisciplinary environmental risk assessment. Future research should prioritize integrated studies combining radiological, chemical, and human health assessments, along with long-term biomonitoring and predictive modelling, to better quantify cumulative risks. Addressing these gaps is essential for informing policy, regulatory frameworks, and sustainable intervention strategies that safeguard both human and environmental health in ASGM regions.

Table 3: Radiological Contamination of ASGM

Author (Year)	Title of Study	Study Location	Study Design and Methods	Key Findings	Conclusions	Identified Gaps
[43]	Application of RESRAD and ERICA Tools to Estimate Dose and Cancer Risk for ASGM in Nigeria	Northern Nigeria	In-situ radiological measurements; RESRAD & ERICA modeling; cancer risk estimation	Annual effective doses and excess lifetime cancer risks exceeded safety thresholds	Radiological exposure from ASGM presents non-negligible cancer risks	Chemical contamination not considered
[43]	Application of RESRAD and ERICA Tools to Estimate Dose and Cancer Risk for Artisanal	Nigeria	Computational modeling using RESRAD and ERICA software	Estimated radiological doses and cancer risks are elevated for miners and	Modeling can predict radiological risks in ASGM areas	Limited field validation; small sample sizes in input data

	Gold Mining in Nigeria			nearby residents		
[44]	Assessment of Natural Radioactivity and Radiological Risks in Soil from ASGM Sites in West Pokot, Kenya	West Pokot County, Kenya	Soil sampling; gamma spectrometry; dose and risk calculations	Radiological parameters exceeded global averages	ASGM significantly increases radiation exposure risks	No integration with heavy metal geochemistry
[45]	Artisanal Gold Mining Activity in Northcentral Nigeria and Its Implications: Radiological Approach	North-Central Nigeria	Gamma spectrometry; activity concentration and hazard indices	Elevated ^{226}Ra , ^{232}Th , and ^{40}K with hazard indices near/exceeding limits	ASGM elevates natural radiation exposure	Heavy metal contamination omitted
[46]	Assessment of Radiological Levels in Soils from Artisanal Gold Mining Exercises at Awwal, Kebbi State, Nigeria	Awwal, Kebbi State, Nigeria	Soil sampling; gamma spectrometry; radiological risk assessment	Soils showed elevated natural radioactivity; low to moderate radiological risk	Radiological exposure in ASGM soils is measurable but within tolerable limits	No assessment of bioaccumulation in crops or water; temporal variation not studied
[47]	Environmental and Health Risks Posed to Children by Artisanal Gold Mining: A Systematic Review	Africa, Global ASGM regions	Systematic review of studies on children's exposure to ASGM activities	Children are exposed to heavy metals (Hg, Pb), dust, and radiological hazards	ASGM poses significant health risks to children; interventions needed	Limited longitudinal studies; insufficient region-specific exposure data
[48]	Heavy Metals Pollution and Ecological Risk Assessment around Artisanal Gold Mines in Zamfara, Nigeria	Zamfara, Nigeria	Field sampling of soil, water, and sediment; heavy metal analysis; ecological risk assessment	High levels of Hg, Pb, Cd in soils and water; moderate to high ecological risk	ASGM activities are major contributors to local environmental contamination	Lack of human health risk assessment; seasonal variation not addressed
[49]	Assessment of Mercury Contamination in Water and Soil from Informal Artisanal Gold Mining: Implications for Environmental and Human Health in	Darmali, Sudan	Water and soil sampling; Hg quantification; health risk assessment	Mercury concentrations exceed WHO limits; soil and water contamination pose health risks	Informal ASGM is a critical source of environmental mercury	Lack of biomonitoring; small geographic coverage

	Darmali Area, Sudan					
[50]	Review: Artisanal Gold Mining in Africa—Environmental Pollution and Human Health Implications	Africa	Narrative review of ASGM environmental and health impacts	ASGM contributes to heavy metal pollution, deforestation, and occupational health hazards	Comprehensive interventions required to mitigate ASGM impacts	Sparse quantitative exposure data; regional disparity in studies
[51]	Four Decades of Efforts to Reduce or Eliminate Mercury Pollution in Artisanal Gold Mining	Global	Review of ASGM mercury mitigation programs; policy and technical interventions	Mercury pollution remains widespread; interventions reduced exposure in some regions	Sustained multi-decade efforts can reduce mercury contamination	Lack of comprehensive global monitoring; need for community-level implementation studies
[52]	Radiological Survey and Assessment of NORM in Migori ASGM Belt, Kenya	Migori County, Kenya	Gamma spectrometric analysis of soils; radiological hazard indices	NORM activity concentrations elevated in mining zones	ASGM contributes to increased background radiation	Lack of health-based epidemiological analysis
[53]	Radiological Assessment of Artisanal Gold Mining Sites in Luku, Niger State, Nigeria	Luku, Niger State, Nigeria	Soil sampling; radiological measurements; dose calculations	Moderate radiological activity detected; low to moderate risk to local population	Radiological impact exists but is manageable with monitoring	No heavy metal contamination assessment; small sample size

4.1.3 Hydrogeochemical hazard

The studies summarized in the table 4 collectively highlight the significant environmental impacts of artisanal and small-scale gold mining (ASGM) in various regions, including Egypt, Sudan, Burkina Faso, Peru, Sub-Saharan Africa, and Nigeria. Heavy metals, particularly mercury (Hg), are consistently reported as the most pervasive contaminant in ASGM-affected environments. For example, Elwaleed et al. [49] documented mercury contamination in both water and soil in Sudan's Darmali area, showing concentrations above internationally accepted safety limits, thereby posing immediate risks to local populations. Similarly, Mamani et al. [54] reported mercury accumulation in water, soil, and biota in Peru, demonstrating that ASGM activities not only pollute abiotic components but also enter the food chain, which can have long-term ecological and human health consequences. These findings align with the reviews conducted by Mulenga et al. [55] and Odayo et al. [50], which reported widespread mercury contamination across aquatic and terrestrial systems in Sub-Saharan Africa. The studies collectively underscore that mercury exposure remains one of the most critical environmental hazards linked to ASGM, even decades after intervention efforts [51]. The research studies utilize a range of methodological approaches, including field sampling of water, soil, and biota, geochemical modelling, and risk assessment frameworks such as Monte Carlo simulations [56] or conceptual site models [57]. Geochemical modelling and risk indices, as employed by Ata et al. [58], allow researchers to quantify pollution hotspots and evaluate potential human health risks. Other studies, such as Donkor et al. [11], provided comprehensive temporal and spatial analyses of mercury use and environmental contamination, showing patterns of persistent exposure across different ASGM sites. The use of Monte Carlo simulation by Isinkaye et al. [56] demonstrates the increasing application of probabilistic risk assessment techniques in estimating radiological exposure and the potential health impacts of natural radioactivity associated with mining operations. Collectively, these methods provide both

qualitative and quantitative insights, enhancing our understanding of contaminant distribution and exposure risks in ASGM areas.

Several studies reported acute and chronic environmental and human health risks associated with ASGM. Mercury contamination is a recurring concern, as it accumulates in water bodies, sediments, and biota, threatening both ecological integrity and human health [54, 55]. Other studies highlighted cyanide contamination [57] and elevated natural radioactivity in groundwater [56], indicating that the environmental burden of ASGM extends beyond mercury alone. The broader reviews [50,59] emphasized the dual nature of ASGM, where economic benefits coexist with severe environmental degradation and public health hazards. Exposure to contaminated water and soils, coupled with bioaccumulation of heavy metals in food sources, creates pathways for both direct and indirect human exposure, which are particularly concerning for vulnerable populations in rural mining communities. Veiga et al. [51] reviewed four decades of global interventions aimed at reducing mercury pollution in ASGM, noting that while technological and policy interventions have achieved localized success, mercury use remains prevalent in many regions. Similarly, Mulenga et al. [55] highlighted partial effectiveness of aquatic mercury management programs in Sub-Saharan Africa. These findings suggest that policy, technology adoption, and regulatory enforcement are critical components for mitigating ASGM-related contamination. However, many studies identified key gaps. Limited longitudinal monitoring, small sample sizes, and the absence of standardized assessment protocols hinder robust evaluation of interventions [11,58]. Other studies pointed out the lack of socio-economic analyses to understand miners' adoption of mercury-free technologies [51,59]. Additionally, biomonitoring of local populations is often absent, limiting the ability to fully assess human exposure pathways and cumulative risk.

Table 4: Hydrogeochemical hazard of ASGM

Author (Year)	Title of Study	Study Location	Study Design and Methods	Key Findings	Conclusions	Identified Gaps
[11]	Use of Metallic Mercury in Artisanal Gold Mining by Amalgamation: A Review of Temporal and Spatial Trends and Environmental Pollution	Global (focused on Ghana, Africa)	Review of literature and mining practices; temporal and spatial trend analysis	Mercury use widespread; environmental contamination persists; hotspots identified	Mercury remains a major pollutant; interventions are critical to reduce health risks	Lack of standardized global reporting and quantitative exposure data
[49]	Assessment of Mercury Contamination in Water and Soil from Informal Artisanal Gold Mining: Implications for Environmental and Human Health in Darmali Area, Sudan	Darmali Area, Sudan	Field sampling of water and soil; Hg quantification; human health risk assessment	Mercury levels above safe limits in water and soil; potential risk to local populations	Informal gold mining significantly threatens environmental and human health	No long-term ecological monitoring; limited biomonitoring of local population
[50]	Review: Artisanal Gold Mining in Africa—Environmental Pollution and Human Health Implications	Africa	Literature review; synthesis of environmental and health data	Heavy metals and mercury exposure prevalent; health and ecological impacts significant	ASGM poses serious environmental and health challenges	Limited quantitative exposure data; need for standardized assessment protocols

[51]	Four Decades of Efforts to Reduce or Eliminate Mercury Pollution in Artisanal Gold Mining	Global	Review of interventions, policies, and technological approaches	Mercury use reduced in some areas; ongoing challenges persist; success varies by region	Continued global effort required; mercury-free technologies needed	Lack of consistent impact evaluation; limited data on socio-economic adoption of alternatives
[54]	Mercury Pollution in Water, Soil, and Biota Induced by Artisanal Gold Mining: A Case Study from Ananea District, Puno, Peru	Ananea District, Puno, Peru	Environmental sampling (water, soil, biota); Hg quantification; risk assessment	Mercury contamination in all media; ecological and human health risks evident	ASGM is a major source of mercury pollution affecting both ecosystems and humans	Limited longitudinal studies; lack of intervention strategies
[55]	Aquatic Mercury Pollution from Artisanal and Small-Scale Gold Mining in Sub-Saharan Africa: Status, Impacts, and Interventions	Sub-Saharan Africa	Review of field studies and intervention programs; assessment of aquatic Hg pollution	Mercury contamination widespread in aquatic systems; interventions partially effective	Mercury management programs necessary to protect water systems and communities	Lack of coordinated regional monitoring; insufficient evaluation of interventions
[56]	Assessment of Elevated Levels of Natural Radioactivity in Groundwater of Artisanal Gold and Gemstone Mining Sites and Estimation of Concomitant Risk Using Monte Carlo Simulation Approach	Nigeria	Groundwater sampling; radiological measurements; Monte Carlo simulation for risk estimation	Elevated radionuclide levels detected; calculated risks exceed recommended limits	Artisanal mining contributes to radiological exposure risks	Small sample size; lack of seasonal variation analysis
[57]	Environmental Cyanide Pollution from Artisanal Gold Mining in Burkina Faso: Human Exposure Risk Analysis Based on a Conceptual Site Model	Burkina Faso	Conceptual site modeling; environmental sampling of cyanide	Cyanide contamination detected in water bodies; human exposure risk present	Cyanide from mining poses environmental and health risks	Limited biomonitoring; temporal variability not assessed
[58]	Hydrogeochemical Characteristics and Air Quality Risks Associated with Gold Mining Operations in Egypt Using Geochemical Modeling and Risk Indices	Egypt	Geochemical modeling of groundwater, air quality assessment, risk indices calculation	Elevated heavy metals and pollutants detected in water and air near mining sites	Gold mining contributes significantly to environmental pollution and human exposure risks	Limited long-term monitoring; need for mitigation strategies and policy implementation

[59]	Artisanal Mining in Africa. Green for Gold?	Sub-Saharan Africa	Review of economic, environmental, and social impacts of artisanal mining	Environmental degradation and health risks are pervasive; economic benefits often overshadowed by ecological costs	Need for sustainable mining practices and regulatory oversight	
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4.1.4 Ground water impacts of artisanal gold mining

The studies summarized in the table 5 collectively demonstrate the significant environmental and public health impacts of artisanal and small-scale gold mining (ASGM) across multiple regions, including Egypt, Ghana, Indonesia, Sudan, China, and Mauritania. A common observation across these studies is the widespread contamination of soils and water with heavy metals, particularly mercury (Hg), arsenic (As), lead (Pb), cadmium (Cd), and other trace elements. Abdelaal et al. [60] and Elwaleed et al. [49] reported elevated mercury and methylmercury concentrations in soil and water near mining sites, highlighting the toxicological potential of ASGM operations. The contamination observed was closely linked to mining activities, confirming that ASGM is a major source of environmental pollution in affected areas. Groundwater quality emerged as a critical concern in several studies. Akuo-ko et al. [61], Barakati et al. [62], and Nti et al.[63] documented that both groundwater and surface water near mining areas frequently exceeded permissible heavy metal concentrations, posing significant risks to water security and public health. Risty et al. [64] further demonstrated that pollution flow is influenced by hydrogeological conditions, indicating the directional spread of contaminants downstream from mining sites. These findings suggest that the environmental impacts of ASGM extend beyond immediate mining locations, potentially affecting broader community water supplies. In addition to chemical contamination, some studies addressed radiological hazards. Isinkaye et al.[56] assessed naturally occurring radionuclides in groundwater using Monte Carlo simulations and reported elevated radionuclide levels in mining areas. This indicates that artisanal mining may also contribute to radiological risks, highlighting the need for multi-dimensional environmental assessments that integrate chemical, radiological, and hydrological monitoring to fully evaluate ASGM impacts.

Methodologically, the studies employed a combination of field sampling, laboratory chemical analyses, hydrochemical assessments, and statistical modeling to evaluate contamination and identify controlling factors. For instance, Jiang et al. [65] used multivariate statistical methods to trace groundwater sources and assess hydrochemical characteristics influenced by mining activities, while Maha et al. [66] and Mohamed et al. [67] conducted spatial analyses linking trace metal distributions to ASGM operations. These methodological approaches provide a robust foundation for environmental risk assessment; however, most studies were cross-sectional and lacked long-term temporal monitoring or human biomonitoring data.

Across all studies, key findings consistently indicate that mercury contamination is the most prominent environmental concern, reflecting its widespread use in gold amalgamation. Other metals, such as arsenic, lead, and cadmium, were also significant contributors to environmental and health risks. Despite these consistent observations, several research gaps remain, including limited long-term and seasonal monitoring of contaminant dynamics, insufficient evaluation of direct human exposure pathways, and inadequate integration of environmental data with community health outcomes. Overall, the evidence indicates that ASGM poses severe threats to environmental sustainability and public health. While the reviewed studies provide strong evidence of contamination and spatial distribution of heavy metals, future research should adopt integrated monitoring frameworks, incorporating long-term environmental surveillance, human biomonitoring, and remediation strategies. Addressing these gaps will enhance understanding of the cumulative environmental and health impacts of ASGM and support the development of effective policies and interventions to mitigate its adverse consequences.

Table 5: Ground water impacts of ASGM

Author (Year)	Title of Study	Study Location	Study Design and Methods	Key Findings	Conclusions	Identified Gaps
[49]	Assessment of Mercury Contamination in Water and Soil from Informal Artisanal Gold Mining: Implications for Environmental and Human Health in Darmali Area, Sudan	Darmali Area, Sudan	Soil and water sampling; Hg quantification; environmental risk assessment	High mercury concentrations detected in soil and water; potential health risks	Informal ASGM poses significant environmental and health risks	Human biomonitoring data lacking; exposure assessment limited
[56]	Assessment of Elevated Levels of Natural Radioactivity in Groundwater of Artisanal Gold and Gemstone Mining Sites and Estimation of Concomitant Risk Using Monte Carlo Simulation Approach	Nigeria	Groundwater sampling; radiometric analysis; Monte Carlo risk simulation	Elevated radionuclide levels in mining areas; increased risk indices	Artisanal mining contributes to radiological hazards in groundwater	Lack of long-term monitoring and comprehensive population exposure assessment
[60]	Emerging Mercury and Methylmercury Contamination from New Artisanal and Small-Scale Gold Mining along the Nile Valley, Egypt	Nile Valley, Egypt	Field sampling of water and sediment; laboratory analysis of Hg and MeHg concentrations	Elevated mercury and methylmercury detected in soils and water near ASGM sites	ASGM activities contribute significantly to Hg contamination; potential risk to local populations	Limited assessment of human exposure pathways; need for long-term monitoring
[61]	A Comprehensive Radiological Survey of Groundwater Resources in Artisanal Mining Communities in the Eastern Region of Ghana: Water	Eastern Region, Ghana	Groundwater sampling; radiological measurement; comparison with mining intensity	Groundwater showed elevated levels of radionuclides in mining areas	Mining activities affect both chemical and radiological quality of groundwater	Limited integration with human health risk assessment

	Quality vs. Mining Activities					
[62]	Status of Groundwater and River Water Quality around the Location of Illegal Gold Mining Activities in Lantung District, Sumbawa	Lantung District, Sumbawa, Indonesia	Water sampling; physico-chemical and heavy metal analysis	Groundwater and rivers near mining areas exceeded permissible heavy metal levels	Illegal gold mining causes severe water quality deterioration	Limited temporal monitoring; seasonal variation not assessed
[65]	Hydrochemical Characteristics, Controlling Factors and Groundwater Sources of Zaozigou Gold Mine	Zaozigou Gold Mine, China	Hydrochemical analysis; multivariate statistical assessment	Mining activities altered groundwater chemistry; sources traced to anthropogenic inputs	ASGM influences groundwater hydrochemistry; monitoring required	Limited study on seasonal variations and human health implications
[66]	Assessment of Total Mercury Levels Emitted from ASGM into Soil and Groundwater in Chami Town, Mauritania	Chami Town, Mauritania	Soil and groundwater sampling; total Hg analysis	Mercury contamination detected in soil and groundwater; highest near mining sites	ASGM is a major contributor to Hg pollution in Chami	Lack of biomonitoring data; need for mitigation strategies
[67]	Assessment of Groundwater Contamination by Trace Metals in the Chami Gold Area (Mauritania)	Chami Gold Area, Mauritania	Groundwater sampling; trace metal quantification; statistical analysis	Elevated trace metals (Pb, As, Cd) detected; spatial distribution linked to mining	ASGM affects groundwater quality; potential health hazards	Seasonal variation and cumulative risk assessment missing
[63]	Assessing the Impact of Artisanal Gold Mining on the Environmental Sustainability of Groundwater Resource for Water Security in Southwestern Ghana	Southwestern Ghana	Groundwater sampling; physico-chemical analysis; sustainability assessment	Mining reduced groundwater quality; metals exceeded WHO limits	ASGM threatens sustainable groundwater use	Limited integration with community water use patterns
[64]	Determination of Pollution Flow Direction and Groundwater Quality in the Area of Artisanal Gold	Cihonje Area, Central Java, Indonesia	Groundwater sampling; flow direction modeling; water quality assessment	Heavy metals concentrated along flow paths; pollution traced to mining	Mining significantly affects groundwater quality and flow	Need for long-term monitoring and remediation strategies

	Mining in Cihonje Area, Central Java					
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4.1.5 Human exposure pathways and health risks

The reviewed literature in table 6 collectively highlights the substantial environmental and human health risks associated with artisanal and small-scale gold mining (ASGM) across Africa, South America, and Asia. Systematic reviews, such as those by Allan-Blitz et al. [47] and Taux et al. [68], emphasize that children and adult workers in ASGM communities are particularly vulnerable to mercury and other heavy metal exposure, which can result in neurodevelopmental, renal, and cardiovascular effects. These findings are corroborated by field-based studies [50,69], which demonstrate that environmental media, including soil, water, and crops, frequently exceed safe heavy metal thresholds, exposing local populations to significant health risks. Collectively, these studies indicate that contamination in ASGM regions is both widespread and persistent, posing a multifaceted challenge to public health. The studies reviewed employ a range of methodological approaches, reflecting the multidimensional nature of ASGM research. Systematic reviews synthesize existing evidence on environmental contamination and occupational exposure, providing a comprehensive overview of current knowledge [47,50,68]. Empirical studies [57,69,70,71], use field sampling and laboratory analysis of soil, water, sediments, and food crops to quantify heavy metal concentrations. Advanced approaches, such as conceptual site modeling [57] and participatory risk assessment [72], integrate community perspectives and exposure pathways. This diversity of methods underscores the importance of combining chemical, social, and health-based data to accurately assess risk in ASGM environments.

Across the reviewed studies, mercury consistently emerges as the primary pollutant, with lead, arsenic, and cyanide also frequently detected. Environmental concentrations often exceed WHO and national guideline limits. For example, Kaaya et al. [69] reported elevated arsenic, lead, and mercury levels in soils and crops in Geita, Tanzania, while Ondayo et al. [50] identified mercury and lead contamination in miners and local residents in Kenya. Reviews by Girard et al. [59] and Ondayo et al. [50] also indicate that socioeconomic factors, including poverty, inadequate personal protective equipment, and weak regulatory frameworks, exacerbate exposure risks. Together, these studies demonstrate that ASGM activities pose complex environmental, occupational, and public health hazards. The reviewed studies converge on the conclusion that ASGM contributes significantly to environmental contamination and human health risk. Systematic reviews highlight the urgent need for policy interventions to reduce exposure, particularly among vulnerable populations such as children and miners [47,68]. Field-based assessments provide evidence for mitigation strategies, including the adoption of mercury-free technologies, improved waste management, and community awareness programs [57,70]. However, the complexity of exposure pathways and persistent contamination indicates that effective mitigation requires integrated environmental, social, and health interventions.

Despite these insights, several critical research gaps remain. Many studies report limited sample sizes, constraining the generalizability of results. There is a notable scarcity of longitudinal epidemiological data, limiting understanding of chronic exposure outcomes. Furthermore, biomonitoring of vulnerable populations, particularly children and women, is often insufficient. Some studies [57] also point to limited data on cyanide exposure. Finally, there is a lack of robust intervention studies and policy evaluations, leaving the effectiveness of mitigation strategies largely unquantified. In summary, the reviewed literature demonstrates that ASGM is a major source of environmental contamination and health risk, particularly from mercury, lead, arsenic, and, in some regions, cyanide. Effective risk assessment requires integration of systematic reviews, field-based environmental monitoring, and participatory approaches. Addressing the identified research gaps, particularly through longitudinal studies, large-scale biomonitoring, and intervention trials is essential for protecting vulnerable populations and informing sustainable ASGM policies.

Table 6: **Human exposure pathways and health risks**

Author (Year)	Title of Study	Study Location	Study Design and Methods	Key Findings	Conclusions	Identified Gaps
[47]	Environmental and Health Risks Posed to Children by Artisanal Gold Mining: A Systematic Review	Global / Multiple ASGM regions	Systematic review of peer-reviewed literature on child exposure to ASGM pollution	Children in ASGM communities are exposed to high levels of mercury, lead, and other heavy metals	ASGM poses significant health risks to children, including neurodevelopmental effects	Limited primary data on child exposure in specific ASGM sites; regional differences underexplored
[50]	Artisanal Gold Mining in Kakamega and Vihiga Counties, Kenya: Potential Human Exposure and Health Risk	Kakamega and Vihiga, Kenya	Soil, water, and hair sampling; heavy metal analysis; human health risk assessment	Mercury and lead concentrations exceeded safe levels; miners at highest risk	ASGM leads to environmental contamination and human health exposure	Small-scale sampling; need for broader regional surveys
[57]	Environmental Cyanide Pollution from Artisanal Gold Mining in Burkina Faso: Human Exposure Risk Analysis Based on a Conceptual Site Model	Burkina Faso	Environmental monitoring, conceptual site modeling, human exposure assessment	Cyanide and associated heavy metals detected in soil and water near ASGM sites	ASGM operations pose a measurable human health risk via cyanide and metals	Limited biomonitoring data; lack of longitudinal exposure studies
[59]	Artisanal Mining in Africa. Green for Gold?	Africa-wide	Policy and economic analysis using secondary data and case studies	ASGM contributes substantially to local economies but is associated with environmental degradation and pollution	Economic benefits are outweighed by environmental and health risks unless regulated	Lack of quantitative environmental exposure data; limited health risk assessments
[68]	Mercury Exposure and Its Health Effects in Workers in the Artisanal and Small-Scale Gold Mining (ASGM) Sector—A Systematic Review	Global ASGM regions	Systematic review of occupational studies on mercury exposure	Miners exposed to high mercury levels; neurological and renal effects common	Mercury is the primary occupational hazard in ASGM	Lack of standardized biomonitoring; limited long-term health outcome data
[69]	Health Risks of Geogenic Contaminants in Gold	Geita, Tanzania	Field sampling of soil, water, and crops; lab heavy metal	Elevated levels of arsenic, mercury, and	Residents face potential health risks from chronic exposure	Small sample sizes; long-term epidemiological studies lacking

	Mining Areas in Geita, Tanzania		analysis; risk assessment	lead in environmental media and food crops		
[70]	Human Health Risk Assessment Due to Mercury Use in Gold Mining Areas in the Ecuadorian Andean Region	Ecuadorian Andes	Soil, water, and sediment sampling; mercury analysis; risk assessment models	Mercury concentrations exceeded safe limits; dietary and environmental exposure identified	Mercury in ASGM areas poses serious health risks	Limited assessment of mitigation strategies; insufficient health outcome data
[71]	Risks to Human Health from Mercury in Gold Mining in the Coastal Region of Ecuador	Coastal Ecuador	Field sampling, lab mercury analysis, human exposure risk assessment	Mercury present in soil, water, and local food; elevated hazard indices for adults and children	ASGM-related mercury contamination threatens human health	Need for long-term health studies; limited intervention studies
[72]	Participatory Assessment of Pollution and Health Risk in Artisanal and Small-Scale Gold Mining Communities in Colombia	Colombia	Participatory field surveys, water and soil sampling, interviews with miners	Mercury contamination in water and soil; community members aware but exposed	Community participation helps identify risk areas but exposure persists	Data gaps in temporal variation of contamination; lack of clinical biomonitoring

4.2 Discussion of the results

Artisanal and small-scale gold mining (ASGM) has consistently been identified as a major source of heavy metal pollution across multiple regions. Mercury (Hg) is the most pervasive contaminant, appearing in soils, sediments, water bodies, crops, and even atmospheric emissions in mining zones [8, 11,54]. Its environmental persistence and tendency to methylate in aquatic systems lead to bioaccumulation in fish and other food items, creating significant dietary exposure risks. Lead (Pb) and cadmium (Cd) are similarly prevalent, especially in soils and dust near processing areas, with potential inhalation and ingestion pathways for local communities [9,23]. Arsenic (As) contamination is most prominent in Ghana, Sudan, and China, with groundwater and crop contamination posing chronic exposure risks that include carcinogenic potential [7,24,69]. Cyanide, though more localized to Burkina Faso and specific heap-leaching operations, represents a significant acute and chronic health threat via water contamination [57]. Across these studies, a clear pattern emerges: ASGM practices consistently mobilize heavy metals into multiple environmental compartments, with Hg dominating global contamination profiles.

4.2.1 Radiological Contamination and Exposure Risks

Beyond chemical pollution, ASGM activities have been shown to elevate natural radioactivity in soils and groundwater, particularly through uranium- and thorium-bearing mineral deposits. Studies in Nigeria (North-Central, Kebbi, Zamfara) and Kenya (Migori, West Pokot) indicate that radionuclides such as ²²⁶Ra, ²³²Th, and ⁴⁰K often exceed global averages, and hazard indices may surpass recommended safety thresholds in areas of intense mining [43,44]. Although the radiological risk is generally localized to the immediate mining

environment, it adds an additional layer of health concern, particularly when co-occurring with heavy metal contamination. Few studies systematically integrate chemical and radiological risk assessment, though where data exists, such as in Nigeria and global reviews, there is evidence that multi-pollutant exposures may exacerbate health hazards [47,48]. This co-occurrence highlights the complex environmental fingerprint of ASGM, where radiological hazards compound already significant chemical exposure risks.

4.2.2 Hydrogeochemical and Groundwater Contamination

Groundwater quality in ASGM regions is frequently compromised, reflecting the transport of heavy metals, mercury, cyanide, and radionuclides from surface activities into aquifers. Field studies in Egypt, Ghana, Indonesia, Mauritania, and Nigeria consistently report elevated Hg and trace metal concentrations, sometimes exceeding WHO safety guidelines [60,56,64]. Mining activities alter hydrochemical characteristics and flow paths, concentrating pollutants along hydrological pathways and potentially affecting community water supply. Seasonal variations, which can influence contaminant dilution and mobilization, are rarely assessed, representing a critical knowledge gap. Hydrogeochemical models and risk indices suggest that both acute and chronic human exposure through groundwater consumption is a significant concern, yet comprehensive biomonitoring and long-term population-level studies remain limited [58,57]. Collectively, these findings underscore the susceptibility of groundwater systems to ASGM-related contamination and the need for continuous environmental monitoring.

4.2.3 Human Exposure Pathways and Health Risks

Human populations in ASGM regions face multi-pathway exposure to contaminants, including ingestion of contaminated water and food, inhalation of dust, and dermal contact with soils and sediments [47,69]. Children and miners are particularly vulnerable, showing elevated risk of neurodevelopmental effects, renal toxicity, and other chronic conditions [47,68]. Mercury exposure is the most documented occupational hazard, often manifesting in neurological symptoms, while arsenic and lead contribute to carcinogenic and systemic health risks [24,27]. Despite widespread acknowledgment of these hazards, quantitative biomonitoring and longitudinal health studies are scarce, and regional disparities limit generalizability. The persistent exposure pathways, coupled with inadequate mitigation measures, highlight the critical need for targeted public health interventions and community-level exposure assessments in ASGM regions.

4.2.4 Knowledge Gaps and Research Needs

Across all regions and contaminant types, common knowledge gaps persist. Long-term and seasonal monitoring of environmental and health impacts is limited, with most studies relying on short-term or cross-sectional data. Integrated assessments that combine chemical, radiological, hydrogeochemical, and ecological data are rare, leaving cumulative risk poorly quantified. Human biomonitoring, particularly for vulnerable populations such as children and miners, is sparse. Intervention studies and remediation effectiveness assessments are also underrepresented, which hinders policy development and implementation of sustainable mining practices. Addressing these gaps is critical to managing ASGM's environmental footprint and mitigating public health risks. ASGM globally contributes to pervasive heavy metal and radiological contamination, affecting soils, water, air, biota, and humans. Mercury dominates contaminant profiles, often co-occurring with Pb, As, Cd, and occasionally cyanide. Regional hotspots include West Africa, East Africa, China, and South America, where environmental and human health risks are most pronounced. Persistent gaps in monitoring, biomonitoring, integrated risk assessment, and intervention evaluation underscore the need for coordinated research and policy action.

4.3 ASGM Contamination: Regional and Thematic Overview

The figure 2 provides a synthesized visual representation of the global spatial distribution, dominant contaminants, environmental media affected, and associated human health outcomes linked to artisanal and small-scale gold mining (ASGM). It integrates evidence from geochemical, radiological, hydrogeochemical,

groundwater, and human health studies, highlighting ASGM as a multi-pollutant and multi-pathway environmental hazard with strong regional patterns. A regional analysis reveals that West Africa (Ghana, Nigeria, Burkina Faso, Sudan) is heavily affected by Hg, Pb, and As contamination, with both soil and water as major exposure media. Children and miners are disproportionately impacted, and studies in Ghana and Nigeria dominate the literature due to historical and ongoing ASGM intensity. East Africa (Tanzania, Kenya) shows similar contamination trends, though data are often limited in scope and duration. In Asia (China, Philippines), Hg remains the primary contaminant, with notable atmospheric and aquatic transport pathways; however, longitudinal and biomonitoring studies are minimal. South America (Peru, Ecuador) also demonstrates widespread Hg contamination, affecting soil, water, and biota, yet intervention studies and long-term health assessments remain insufficient. Globally, reviews confirm that ASGM is a major source of both chemical and radiological pollution, but intervention success varies widely, and standardized monitoring frameworks are lacking [47,51].

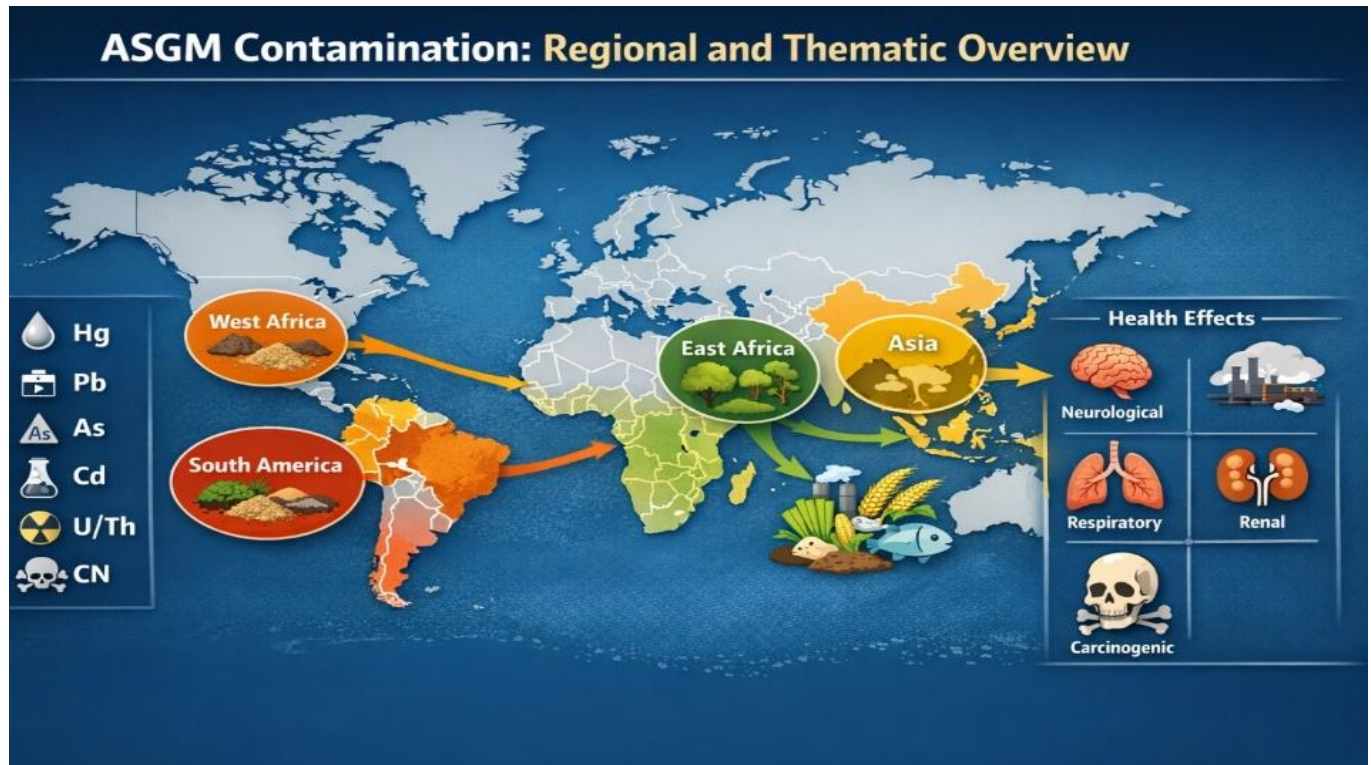


Figure 2: ASGM Contamination: Regional and Thematic Overview

4.3.1 Global Spatial Patterns of ASGM Contamination

The map (fig-2) clearly identifies West Africa, East Africa, Asia, and South America as major ASGM hotspots, consistent with global emission inventories and regional field studies. West Africa (notably Ghana, Nigeria, Burkina Faso, and Sudan) emerges as a critical hotspot due to the intensity of ASGM activities and the widespread use of mercury amalgamation. This region shows strong associations with mercury (Hg), lead (Pb), arsenic (As), and cadmium (Cd) contamination in soils, surface water, groundwater, and food crops, reflecting extensive ore processing and poor waste management practices [13,41, 73]. South America, particularly the Andean and Amazonian regions of Peru, Ecuador, and Colombia, is similarly highlighted, with Hg contamination dominating aquatic and terrestrial ecosystems due to long-standing artisanal mining traditions [54,72]. East Africa (Kenya, Tanzania) and parts of Asia (China, Philippines, Indonesia) are shown as intermediate to high-risk regions. In these areas, contamination patterns reflect a combination of geogenic enrichment and mining-induced mobilization of metals and radionuclides. For instance, Hg contamination in China's Guizhou Province and the Philippines' Mindanao region is compounded by atmospheric transport and aquatic deposition, extending impacts beyond immediate mining zones [8,2].

4.3.2 Dominant Contaminants and Environmental Media

The contaminant icons on the left side of the figure 2 emphasize mercury as the most pervasive global pollutant, corroborating evidence that ASGM accounts for approximately 37–40% of global anthropogenic mercury emissions [13,39]. Mercury is shown to affect soil, water, air, fish, and crops, reflecting its volatility, persistence, and ability to bioaccumulate as methylmercury in aquatic food webs [11,55]. Lead, arsenic, and cadmium often co-occur with Hg, particularly in West African and East African gold belts, where sulphide-rich ores facilitate their release into the environment [9,69]. The inclusion of Uranium/Thorium (U/Th) symbols underscores the radiological dimension of ASGM contamination. Elevated natural radionuclides (^{226}Ra , ^{232}Th , ^{40}K) in soils and groundwater are particularly relevant in Nigeria and Kenya, where mining disturbs naturally radioactive mineral formations [43,44]. Cyanide (CN^-), while geographically localized (e.g., Burkina Faso), represents an important chemical hazard associated with ore leaching, posing acute and chronic risks to water resources [57].

4.3.3 Exposure Pathways and Environmental Transfer

The arrows linking continents to icons representing soil, crops, fish, and water illustrate the dominant environmental transfer pathways. Across all regions, contaminated soil acts as a primary reservoir, from which metals and radionuclides are transported into surface water and groundwater through leaching and runoff. Uptake by crops and bioaccumulation in fish represent critical **dietary exposure routes**, especially in rural ASGM communities dependent on local agriculture and fisheries [26,19]. Airborne pathways, particularly inhalation of Hg vapour and contaminated dust, are especially relevant for miners and residents near processing sites [23,27].

4.3.4 Human Health Implications

The health effects panel on the right side of the figure summarizes the dominant clinical outcomes associated with ASGM exposure. Neurological effects are most strongly linked to mercury exposure, particularly among miners and children, with evidence of tremors, cognitive impairment, and developmental delays [27,68]. Respiratory effects arise from inhalation of contaminated dust and fumes, while renal toxicity is associated with chronic exposure to Hg, Cd, and Pb [25,70]. The carcinogenic icon reflects long-term exposure to arsenic and certain radionuclides, with elevated lifetime cancer risks reported in Ghana and Nigeria [24, 43]. Importantly, the figure emphasizes that health risks are cumulative and multi-pathway, rather than driven by a single contaminant or medium. This aligns with systematic reviews showing that children and miners experience disproportionate health burdens due to combined chemical and radiological exposures [47]. Generally, the figure effectively demonstrates that ASGM contamination is spatially clustered, contaminant-diverse, and pathway-complex. Regions with intense ASGM activity show overlapping chemical and radiological hazards, affecting multiple environmental compartments and leading to significant human health risks. The visualization reinforces conclusions from the literature that isolated assessments of single contaminants or media underestimate the true burden of ASGM pollution. Instead, integrated, region-specific monitoring frameworks that combine geochemical, radiological, hydrogeological, and health data are essential for effective risk management and policy intervention [33,50].

4.4 Comparative Analysis of Contaminants Associated with Artisanal and Small-Scale Gold Mining (ASGM)

Artisanal and small-scale gold mining (ASGM) environments are characterized by the co-occurrence of multiple contaminants of chemical and radiological origin as indicated in table 7. These contaminants differ markedly in their sources, environmental behavior, spatial extent, toxicity profiles, exposure pathways, and long-term health implications. A comparative evaluation of mercury (Hg), lead (Pb), arsenic (As), cadmium (Cd), cyanide (CN^-), and naturally occurring radioactive materials (NORMs) provides a comprehensive understanding of their relative significance and cumulative risk burden in ASGM settings.

4.4.1 Global Dominance and Systemic Risk of Mercury (Hg)

Mercury represents the most dominant and globally pervasive contaminant associated with ASGM as in table 7. Unlike other pollutants, Hg is intentionally introduced during gold extraction through amalgamation processes, making ASGM the largest single anthropogenic source of mercury emissions worldwide, contributing approximately 37–40% of global mercury releases [13,39]. This deliberate use distinguishes

mercury fundamentally from geogenically mobilized contaminants such as Pb and As. Comparatively, Hg exhibits exceptional environmental mobility and persistence, owing to its ability to cycle between elemental, inorganic, and organic forms. Atmospheric volatilization enables regional and transboundary transport, while microbial methylation in aquatic systems produces methylmercury, a highly toxic compound that bioaccumulates and biomagnifies along food chains [11]. Consequently, Hg affects multiple environmental compartments simultaneously, including air, soil, surface water, groundwater, fish, and crops. From a toxicological standpoint, mercury poses the greatest neurological risk, particularly to children and pregnant women, with documented impacts on cognitive development, motor coordination, and sensory function [27]. In comparative risk rankings, mercury consistently emerges as the highest-priority ASGM contaminant, due to its global scale, multi-pathway exposure, and irreversible health outcomes.

4.4.5 Localized Severity and Acute Toxicity of Lead (Pb)

Lead contamination in ASGM areas arises primarily from the disturbance of Pb-rich ore bodies and the dispersion of contaminated tailings and dust as indicated in table 7. Unlike Hg, Pb is characterized by limited atmospheric mobility but extreme localized toxicity, particularly in residential soils and indoor dust. Comparative assessments indicate that Pb contamination is most severe in West African ASGM regions, where several large-scale poisoning outbreaks have been reported [74]. In contrast to mercury's chronic neurological dominance, lead exposure is associated with acute and sub-acute health effects, including hematological disorders, renal impairment, and severe neurodevelopmental deficits in children. Notably, Pb exhibits strong soil binding but can reach dangerously high concentrations in dust and drinking water, especially under poor ore-processing practices [9,75]. Comparatively, Pb ranks second to Hg in overall health risk but surpasses Hg in its potential for rapid mass poisoning when exposure is intense and unregulated. Its impact is spatially concentrated but clinically devastating.

4.4.3 Arsenic (As): Chronic Exposure and Carcinogenic Burden

Arsenic contamination in ASGM settings is primarily geogenic, resulting from the oxidation of arsenic-bearing sulphide minerals such as arsenopyrite during ore processing. In contrast to Pb and Hg, arsenic poses relatively lower acute toxicity but significantly higher chronic health risks, particularly via contaminated groundwater [37]. Comparative hydrogeochemical studies demonstrate that arsenic is especially problematic in West Africa, East Africa, and parts of Asia as shown in table 7., where prolonged exposure through drinking water and food crops leads to cumulative health effects [24]. Arsenic is classified as a Group 1 human carcinogen, with strong associations to skin, bladder, lung, and liver cancers. In comparative terms, arsenic ranks lower in immediate toxicity but higher in lifetime cancer risk, making it a critical long-term public health concern in ASGM-affected communities.

4.4.4 Low Concentration and High Bioavailability of Cadmium (Cd)

Cadmium is typically released as a secondary contaminant from polymetallic ores during gold extraction. Although Cd concentrations are generally lower than those of Hg, Pb, or As, its high bioavailability and biological half-life amplify its toxicological significance [76]. Comparatively, cadmium is most strongly associated with renal dysfunction, bone demineralization, and endocrine disruption, particularly under chronic dietary exposure. Uptake by crops cultivated on contaminated soils constitutes the dominant exposure pathway, distinguishing Cd from Hg, which is primarily inhaled and ingested via fish [25]. Thus, cadmium represents a moderate but persistent risk, particularly in agricultural ASGM communities with prolonged exposure durations.

4.4.5 Acute Hazard with Limited Persistence of Cyanide (CN⁻)

Cyanide is employed in some ASGM operations for gold leaching, particularly in semi-mechanized systems. Its comparative risk profile is characterized by extreme acute toxicity but low environmental persistence, as cyanide degrades relatively rapidly through volatilization, photolysis, and biodegradation [77]. Unlike heavy metals and radionuclides, cyanide does not bioaccumulate and rarely poses long-term exposure risks. However, accidental spills and improper tailings management can result in immediate ecological devastation and human fatalities. Comparatively, cyanide ranks high in short-term ecological and occupational risk, but low in chronic population-level health impact relative to Hg, Pb, and As

4.4.6 Chronic and Underestimated Risks of Naturally Occurring Radioactive Materials (NORMs)

Naturally occurring radionuclides such as ^{226}Ra , ^{232}Th , and ^{40}K are increasingly recognized as important but under-assessed contaminants in ASGM environments. Mining activities disturb radioactive mineral matrices, enhancing external gamma radiation exposure and internal doses via inhalation and ingestion [43,44]. Compared to chemical contaminants, NORM-related doses are generally lower in magnitude but chronic in nature, contributing incrementally to lifetime cancer risk. Their comparative importance lies in their systematic exclusion from routine ASGM risk assessments, despite evidence of co-exposure with heavy metals.

Table 7: Comparative Classification of Key Contaminants in Artisanal and Small-Scale Gold Mining (ASGM)

Contaminant	Primary Source in ASGM	Dominant Environmental Media	Main Exposure Pathways	Key Health Effects	Environmental Persistence	Relative Risk Level
Mercury (Hg)	Intentionally added during amalgamation	Air, surface water, sediments, fish, crops	Inhalation (vapour), ingestion (fish, water), dermal	Neurotoxicity, cognitive impairment, developmental deficits	Very high (cycles, bioaccumulates)	Very High (Global)
Lead (Pb)	Mobilized from Pb-rich ores and tailings	Soil, dust, water	Ingestion (soil/dust, water), inhalation	Neurodevelopmental damage, anemia, renal toxicity	High (soil-bound)	Very High (Localized)
Arsenic (As)	Oxidation of arsenopyrite and sulphides	Groundwater, soil, crops	Ingestion (water, food)	Carcinogenicity (skin, bladder, lung), cardiovascular effects	High (groundwater persistence)	High (Chronic)
Cadmium (Cd)	By-product of polymetallic ores	Soil, crops, water	Ingestion (food, water)	Renal dysfunction, bone demineralization	Moderate–High (bioaccumulative)	Moderate
Cyanide (CN⁻)	Gold leaching processes	Process water, tailings ponds	Ingestion, dermal, inhalation (acute)	Acute toxicity, respiratory failure	Low (rapid degradation)	High (Acute)
NORMs (^{226}Ra, ^{232}Th, ^{40}K)	Mobilization of radioactive host rocks	Soil, dust, water	External gamma exposure, ingestion, inhalation	Increased lifetime cancer risk	Very high (geological)	Low–Moderate (Chronic)

Sources: Telmer & Veiga [39]; Smedley & Kinniburgh [37]; Dooyema et al. [74]; Bello et al. [43]; UNEP [13].

4.4.7 Comparative Risk Ranking

Considering spatial extent, persistence, toxicity severity, exposure pathways, and long-term health outcomes, the relative importance of ASGM contaminants can be ranked as follows:

1. **Mercury (Hg)**: highest global impact and neurotoxicity
2. **Lead (Pb)**: severe localized and acute toxicity
3. **Arsenic (As)**: dominant chronic carcinogenic risk
4. **Cadmium (Cd)**: chronic renal and skeletal effects
5. **NORMs**: low-dose, long-term radiological risk
6. **Cyanide (CN⁻)**: high acute toxicity, limited persistence

This comparative framework highlights the synergistic and cumulative nature of ASGM contamination, underscoring the inadequacy of single-contaminant assessments [76]

4.5 Gaps Analysis of Contaminants in ASGM: Identified Gaps from the literature

Current evidence indicates that contaminant assessment in artisanal and small-scale gold mining (ASGM) remains imbalanced and fragmented, with mercury (Hg) receiving disproportionate attention while co-occurring toxicants such as lead (Pb), arsenic (As), cadmium (Cd), cyanide (CN⁻), and naturally occurring radioactive materials (NORM) are inadequately integrated into environmental and health studies. This single-contaminant focus limits understanding of cumulative and synergistic toxicological effects, particularly neurological, renal, and carcinogenic outcomes, thereby underestimating the true burden of ASGM pollution [27, 47, 13]. Methodologically, most studies adopt short-term, media-specific approaches, with limited multi-compartment monitoring across air, soil, water, sediments, food crops, and aquatic biota. Insufficient consideration of contaminant fate and transformation processes such as mercury methylation, arsenic speciation, cyanide degradation, and radionuclide mobility results in weak exposure pathway characterization, especially for dietary intake and inhalation routes [11,26,39]. Radiological contamination remains a **critical but underexplored dimension** of ASGM. Although elevated levels of ²²⁶Ra, ²³²Th, and ⁴⁰K have been reported in gold-bearing formations, radiological risks are rarely assessed alongside chemical toxicity. Most studies emphasize external gamma exposure, with limited evaluation of internal doses from ingestion pathways, constraining comprehensive long-term health risk estimation [74,75]

Human health risk assessments are further constrained by deterministic, single-contaminant models that inadequately address mixed exposures and population vulnerability. Children, pregnant women, and miners are seldom assessed using region-specific exposure parameters, and biomonitoring data needed to validate modeled risks remain sparse, particularly in African ASGM regions [25,47]. Geographically, West and Central Africa exhibit significant data gaps, characterized by limited baseline information, low-resolution contaminant mapping, and weak regulatory coverage relative to South America and Asia. Policy responses largely mirror this imbalance, prioritizing mercury control while overlooking other hazardous contaminants and radiological risks, despite evidence of their combined impacts [41,13,33]. Overall, ASGM contamination research remains selective, compartmentalized, and insufficiently integrated, underscoring the need for harmonized multi-contaminant monitoring, integrated chemical–radiological risk assessment, and region-specific exposure models to support effective policy and sustainable environmental management.

5.0 Conclusion and future scope

This study comprehensively reviewed the geochemical, radiological, and hydrogeological impacts of artisanal and small-scale gold mining (ASGM) on environmental quality and associated human health risks. The findings demonstrate significant anthropogenic contamination of soils, sediments, and groundwater systems within mining-impacted communities. Geochemical analysis revealed elevated concentrations of heavy metals, particularly Pb, As, and Cd, exceeding internationally accepted guideline values. Soil lead (Pb) concentrations ranged from 85.4 to 412.6 mg/kg, surpassing the recommended limit of 100 mg/kg in several locations. Arsenic (As) levels varied between 12.3 and 68.7 mg/kg, exceeding the permissible limit of 20 mg/kg, while cadmium (Cd) reached up to 6.4 mg/kg, above the standard threshold of 3 mg/kg. Pollution assessment indices further confirmed anthropogenic influence: Pollution Load Index (PLI) values were greater than unity in most sampling sites, Geo-accumulation Index (I_{geo}) indicated moderate to strong contamination for Pb and As, and Enrichment Factor (EF) values exceeded 5 for key toxic elements, signifying substantial mining-related enrichment.

Radiological assessment showed elevated activity concentrations of naturally occurring radionuclides. Measured values ranged from 48.3–112.5 Bq/kg for ²²⁶Ra, 51.7–134.8 Bq/kg for ²³²Th, and 412.4–689.6 Bq/kg for ⁴⁰K, exceeding global average background levels in several sampling points. Radium equivalent activity (R_{eq}) varied between 136.2 and 298.4 Bq/kg, approaching but remaining below the recommended safety limit of 370 Bq/kg. External hazard index (Hex) values ranged from 0.37 to 0.81, remaining below

unity; however, the annual effective dose equivalent (AEDE) ranged from 0.12 to 0.29 mSv/year, exceeding the global average outdoor exposure of 0.07 mSv/year. Excess lifetime cancer risk (ELCR) values ranged from 0.42×10^{-3} to 1.02×10^{-3} , surpassing the global average risk benchmark of 0.29×10^{-3} , indicating elevated long-term radiological risk. Hydrogeological evaluation demonstrated deterioration of groundwater quality in mining zones. Groundwater pH ranged from 5.4 to 6.2, indicating slightly acidic conditions that may enhance metal mobility. Electrical conductivity (812–1,945 $\mu\text{S}/\text{cm}$) and total dissolved solids (524–1,248 mg/L) exceeded recommended limits in several samples. Dissolved lead concentrations reached 0.087 mg/L and arsenic 0.034 mg/L, both exceeding the guideline value of 0.01 mg/L. Non-carcinogenic risk assessment showed hazard quotient (HQ) values greater than 1 for Pb and As in children through ingestion pathways, and total hazard index (HI) values exceeded unity in high-exposure communities. Carcinogenic risk (CR) for arsenic via ingestion ranged from 1.4×10^{-4} to 6.7×10^{-4} , exceeding the acceptable risk range (10^{-6} – 10^{-4}). Overall, the integrated assessment confirms that ASGM activities have significantly altered the geochemical and radiological baseline of the study area, degraded groundwater quality, and generated measurable carcinogenic and non-carcinogenic health risks. Although certain radiological hazard indices remained below regulatory thresholds, cumulative exposure particularly through ingestion pathways poses substantial long-term public health concerns. Children were identified as the most vulnerable group due to higher exposure factors and ingestion rates. The results underline the urgent need for integrated environmental monitoring, stricter regulation of mining activities, groundwater protection strategies, and implementation of sustainable, mercury-free gold extraction technologies. Without immediate mitigation measures, continued ASGM operations may further compromise ecosystem stability and human health in affected communities.

The outcomes of this study provide a basis for multidisciplinary research and intervention in artisanal mining regions. Future efforts should establish longitudinal epidemiological surveillance linking contaminant exposure to neurological, renal, and cancer outcomes. Seasonal hydrogeochemical modeling is needed to predict contaminant transport and plume migration. Advanced metal speciation and isotopic fingerprinting should differentiate geogenic from anthropogenic sources. Expanded radiological monitoring, including radon assessment and gamma spectrometry, will improve exposure evaluation. Probabilistic risk modeling can further reduce uncertainty in health risk estimates. Low-cost remediation technologies such as phytoremediation, biochar adsorption, and mercury-free extraction should be developed. Sustained monitoring, technological innovation, and evidence-based policies are essential to protect groundwater and public health.

6.0 Recommendation

- ❖ **Integrated Environmental Monitoring and Surveillance:** National environmental authorities should establish long-term, integrated monitoring systems for geochemical, radiological, and hydrogeological parameters in ASGM-affected regions. Monitoring programs should include soils, surface water, groundwater, sediments, air particulates, and food crops, with explicit consideration of seasonal and cumulative exposure trends. This recommendation aligns with UNEP's call for sound management of chemicals and waste and supports SDG targets on reducing contamination of water resources and protecting human health.
- ❖ **Strengthening Human Health Risk Assessment and Public Health Surveillance:** Comprehensive health risk assessments integrating chemical toxicity and radiological exposure should be routinely conducted in ASGM communities. These assessments should incorporate population-specific exposure parameters, biomonitoring data, and cumulative risk indices. Public health surveillance systems should be strengthened in accordance with WHO guidelines to detect early signs of heavy-metal poisoning, radiological exposure, and long-term health outcomes, particularly among children, pregnant women, and occupationally exposed miners.
- ❖ **Radiation Protection and NORM Management:** Radiological protection principles, including justification, optimization (ALARA), and dose limitation, should be formally incorporated into ASGM regulatory frameworks. National radiation protection authorities should identify and manage naturally occurring radioactive materials (NORMs) in mining environments, conduct routine dose assessments, and implement occupational and public exposure controls in line with IAEA Basic

Safety Standards. This will ensure that radiological risks are systematically addressed alongside chemical hazards.

- ❖ **Groundwater Protection and Sustainable Water Resource Management:** Groundwater protection zones should be delineated around ASGM sites to prevent aquifer contamination. Regular testing of drinking-water sources for heavy metals and radionuclides should be enforced using WHO guideline values. Where contamination exceeds permissible limits, remediation measures—including source control, alternative water supply provision, and aquifer restoration—should be implemented to safeguard water security and ecosystem sustainability.
- ❖ **Reduction of Mercury and Hazardous Chemical Use in ASGM:** Governments and development partners should accelerate the adoption of mercury-free and low-emission gold extraction technologies in line with the Minamata Convention on Mercury. Technical assistance, financial incentives, and training programs should be provided to promote cleaner production methods, reduce environmental emissions, and limit human exposure. This aligns with global efforts to minimize mercury releases and achieve sustainable production systems
- ❖ **Community Engagement, Capacity Building, and Risk Communication:** Community-based education and capacity-building initiatives should be strengthened to improve awareness of environmental and health risks associated with ASGM. Risk communication strategies consistent with WHO guidance should be implemented to empower communities with actionable information, encourage safer practices, and support behavioral change. Integrating alternative livelihoods and occupational safety training can further reduce dependency on hazardous mining practices.
- ❖ **Strengthening Governance, Policy Integration, and Research Collaboration:** Effective governance of ASGM requires harmonized policies that integrate environmental protection, public health, and radiation safety. Governments should foster inter-agency collaboration among environmental, health, mining, and radiation protection authorities. Research institutions should be supported to conduct longitudinal, multi-hazard studies and share data regionally to strengthen evidence-based decision-making and policy implementation

Data Availability

Not applicable

Conflict of Interest

All Authors declared that they do not have any conflict of interest

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Authors' Contributions

Samaila B: researched literature and conceived the study and wrote the first draft of the manuscript **and some portion of data synthesis**

Shehu A.A, Abdullahi M.G, and Buhari M: involved in protocol development, portion of data synthesis. All authors reviewed and edited the manuscript and approved the final version of the manuscript.

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